Searches for gravitational waves transients in the LIGO and VIRGO data

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SEARCHES FOR GRAVITATIONAL WAVE TRANSIENTS IN THE LIGO AND VIRGO DATA

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In 2011, the Virgo gravitational wave (GW) detector will definitively end its science program following the shut-down of the LIGO detectors the year before. The years to come will be devoted to the development and installation of second generation detectors. It is the opportune time to review what has been learned from the GW searches in the kilometric interferometers data. Since 2007, data have been collected by the LIGO and Virgo detectors. Analyses have been developed and performed jointly by the two collaborations. Though no detection has been made so far, meaningful upper limits have been set on the astrophysics of the sources and on the rate of GW events. This paper will focus on the transient GW searches performed over the last 3 years. This includes the GW produced by compact binary systems, supernovae core collapse, pulsar glitches or cosmic string cusps. The analyses which have been specifically developed for that purpose will be presented along with the most recent results.

1 Introduction

Gravitational waves (GW) were predicted by Albert Einstein [1] with his theory of general relativity. It shows that an asymmetric, compact and relativistic object will radiate gravitationally. The waves propagate with a celerity c and their amplitude is given by the dimensionless strain h which can be projected over two polarizations h_+ and $h_\times$. The existence of GW was indirectly confirmed through observations on the binary pulsar PSR 1913+16 discovered in 1974. This binary system has been followed-up over more than 30 years and the orbit decay can be fully explained by the energy loss due to the gravitational wave emission [2]. The great challenge of this century is to be able to detect gravitational waves directly by measuring the space-time deformation induced by the wave. The Virgo [3] and the two LIGO [4] interferometric detectors are designed to achieve this goal. Thanks to kilometric arms, Fabry-Perot cavities, sophisticated seismic isolation, a high laser power and the use of power-recycling techniques, the LIGO and Virgo detectors were able to reach their design sensitivity which is to measure h below 10^{-21} over a wide frequency band, from tens to thousands of Hz (and below 10^{-22} at a few hundreds Hz). Such sensitivity over a large range of frequencies offers the possibility to detect gravitational waves originating from various astrophysical sources which will be described in Section 2.

The searches for GW in LIGO-Virgo were historically divided into four analysis groups. The physics of these groups does not really match the type of GW sources but rather the expected signals. This has the advantage to develop efficient searches adapted to the signal seen in the detector. The CBC group is specifically searching for signals resulting from the last instants of the coalescence and the merging of compact binary systems of two neutron stars, two black holes or one of each. The expected signal is well-modeled, especially the inspiral part, so that the searches are designed to be very selective. On the contrary, the burst group performs more generic searches for any type of sub-second signals. This unmodeled approach offers a robustness to the analyses and remains open to the unexpected. Doing so, the burst group covers a large variety of GW sources for which the expected signals are poorly known. This includes the asymmetric core bounce of supernovae, the merging of compact objects, the star-quakes of neutron stars or the oscillating loops of cosmic strings. This paper will focus on the work performed within the CBC and the burst group and present the searches for short-duration GW signals. C. Palomba will describe the searches for continuous signals and for a stochastic background of GW [5]. Section 3 will detail the different aspects of a multi-detector GW transient search while Section 4 will highlight some of the latest results of the analyses.

Very early on, the Virgo and LIGO collaborations chose to share their data and to perform analyses in common in order to maximize the chance of detection. Indeed, having several detectors in operation presents many advantages such as performing coincidences, reconstructing the source location, having a better sky coverage or estimating the background for analyses. This close collaboration started in 2007 with the Virgo first science run VSR1 (2007) and LIGO S5 (2005-2007) run and continued until recently with the following science runs VSR2 (2009), VSR3 (2010) and S6 (2009-2010). In October 2010, the LIGO detectors shut-down to install the second generation of detectors which should resume science in 2015. Virgo will perform one more science run, VSR4, during the summer jointly with the GEO 600 [6] detector in Germany. After that, Virgo will start the preparation for the next phase with Advanced Virgo.

As the first generation of interferometers is about to take an end, the analyses performed so far were not able to claim a detection. However it was possible to set astrophysically relevant upper limits and this paper will present some of them. Moreover the pioneering work performed to build efficient analyses pipelines will be a great strength for the Advanced detector era and the first steps of gravitational wave astronomy.

2 Sources, signals and searches

2.1 The coalescence of binary objects

The coalescence of stellar compact binary systems is often seen as the most promising candidate for a first detection. Indeed, such objects have been extensively studied and the expected waveform is rather well-modeled. The inspiral phase, up to the last stable circular orbit, can be reliably described with a post-Newtonian approximation [7]. The signal is expected to sweep upwards in frequency and to cross the detector bandwidth for a short period of time (from a few ms to tens of s). This is followed by the merger of the two bodies whose waveform can be derived from numerical relativity [8] even though this part of the waveform is the least known of the evolution of the binary. Finally, the resulting black hole is excited and loses part of its energy by radiating gravitationally. Black hole pertubation theory is well able to predict the ringdown waveform [9] and the signal is expected to be in the detector sensitive band for masses larger than 100 $M_\odot$.

The search for coalescence signals, led by the CBC group, takes two free parameters into account: the masses of the two binary components. The low-mass search covers a total mass range between 2 and 35 $M_\odot$ where most of the energy is contained in the inspiral phase. As a complement, the high-mass search probes the 25-100 $M_\odot$ total mass region where the signal-to-noise ratio is significant mostly during the merger and ringdown phase. A ringdown-only search is also performed for very high-mass systems (75-750 $M_\odot$) in which case it is possible to use the spin as an additional parameter. The merger and the ringdown signals are also included in the burst searches. The robust nature of the burst analyses offers a nice complement to the CBC searches, especially for the merger phase for which the waveform is less reliable.

Astrophysical rates for compact binary coalescence are still uncertain since they are based on a few assumptions like the population of observed double pulsars in our galaxy. A plausible rate for the coalescence of two neutron stars could be somewhere between 0.01 to 10 Myr^{-1} Mpc^{-3}. These numbers offers a chance for a detection which could span between 2×10^{-4} and 0.2 events per year [10] with the initial detector sensitivities.

2.2 Supernovae core collapse

The core bounce of supernovae could also be an interesting source of GW bursts. In this case, the GW production is a complex interplay of general relativity, nuclear and particle physics. Recent studies [11] show that various emission mechanisms could come into play. The coherent motion of the collapsing and bouncing core during the proto-neutron star formation could be asymmetric enough to produce GW. Then the prompt convective motion behind the hydrodynamic shock in the central part of the star due to non-axisymmetric rotational instabilities could also trigger some GW radiation. Recent 2- or 3-dimensional simulations [11] are able to extract complex waveforms but they are extremely parameter-dependent and not robust enough to be used directly in a GW search. In this case again, the burst's unmodeled searches are well-suited. Some studies are in progress to decompose the supernova signatures over a basis of main components which could be then searched in the data [12].

2.3 Isolated neutron stars

Instabilities of isolated neutron stars can also produce GW bursts which could be detected by earth-based interferometers. The invoked mechanism corresponds to the excitation of quasi-normal mode oscillations which couple to GW emission. This excitation could occur as a consequence of flaring activity in soft-gamma repeaters (SGR) resulting from intense magnetic fields [13]. Another possibility comes from the merging of a binary system of two neutron stars. In that case a massive neutron star can be formed. Often excited, it could radiate gravitational waves. Fractures or star-quakes of the neutrons star crust are other possible scenarios for the quasi-normal mode oscillations of the star. F-modes oscillations are the preferred mechanism to produce GW in case of neutron stars. Hence, ringdown waveforms are often used in the searches with a high frequency (from 500 Hz to 3 kHz) and a short damping time (from 50 ms to 500 ms).

2.4 Cosmic strings

The hypothetic existence of cosmic strings [14] could be proven by looking for a signature in the GW spectrum. Indeed, gravitational radiation is the main mechanism for the cosmic string network to lose its energy. When intersecting with each other, strings can form loops which oscillate and produce some cuspy features with a strong Lorentz boost. Cosmic string cusps are therefore a powerful source of GW. Gravitational waveforms are very well predicted [15] and this motivates a dedicated search in the LIGO/Virgo data. In case of no detection, it is possible to set constraints on the string tension which is the main parameter to describe the cosmic string network.

2.5 External triggers

GW emission often results from violent events in the universe. Therefore, these events could also be seen through other channels like electro-magnetism or neutrino emission. The coincidence of a GW event with another type of trigger could critically increase the confidence into the veracity of the event. Moreover the knowledge of the position and/or the time of the event can considerably enhance the sensitivity of the searches. For instance, a gamma-ray burst (GRB) trigger could be an indication that either a binary system merged or a hyper-massive star collapsed. Dedicated analyses over GRB triggers are performed and are presented by M. Was in these proceedings [16].

3 How to extract a GW signal

3.1 Trigger production

As discussed above, many LIGO/Virgo GW searches benefit from the knowledge of the expected waveform. In this case, match-filtering techniques can be used to produce the GW triggers. One first needs to define a template bank where the reference waveforms are covering the parameter space (the component masses for the CBC searches, for example). The distance from one template to the next must be small enough to insure a negligible loss of efficiency but large enough to limit the total number of templates and the computational cost. Then each template is slid over the detector gravitational wave strain $h_{det}(t)$ and the match between the two is computed as a function of time. If this match exceeds a given threshold then a trigger is produced and a signal-to-noise ratio (SNR) is defined.

Most of the burst searches cannot rely on a modeled waveform. The main procedure is to perform a time-frequency analysis. It consists in tiling the time-frequency plane and in looking for an excess of energy in clusters of pixels. Again, a threshold on the energy is set to define triggers.

With an ideal detector, if no GW event is present in the detection strain, the distribution of the SNR should follow a Gaussian statistic. Then a GW event could be detected if its SNR is much larger than the noise SNR distribution. In reality the noise of the detector displays a non Gaussian behavior and the tail of the distribution is composed by many detector artefacts called glitches. Therefore, using only a single detector output, a genuine GW event cannot be disentangled from the noise. When performing a multi-detector analysis, it is possible to set in coincidence different parameters of the search like the time of the trigger or any discriminative variables describing the event. This significantly reduces the tail of the background. However the remaining distribution of events is still not Gaussian and the accidental background distribution needs to be evaluated to quantify confidence of a given event.

3.2 Background estimation

There is a reliable way to evaluate the accidental background distribution when performing a multi-detector analysis. It consists in time-sliding the data of one detector with respect to the other and looking at the time-coincident triggers which cannot contain any real signal. This gives a fair estimation for the background provided that the time shift is larger than the duration of the expected signals and that the noise is locally stationary. With the resulting distribution one can set a detection threshold corresponding to a fixed false alarm rate.

3.3 Data quality

After having performed coincidences between detectors, the background tail is still the main limiting factor for the searches. It is crucial to understand the origin of the glitches to remove them safely and to be able to lower the detection threshold as much as possible. The data quality groups in Virgo [17] and LIGO [18] play a major role in the analysis. They study the couplings between the detection channel and the auxiliary channels to define efficient vetoes to reduce the number of glitches in the tails. Interferometers are sensitive instruments to the environment so it is imperative to monitor disturbances of different natures: acoustic, magnetic, mechanical etc. Then selective vetoes based on environmental channels are produced to increase the sensitivity of the searches.

3.4 Upper limits

Until now, no GW detection has been made. However upper limits can be obtained provided that the efficiency of the search is known. To achieve this, analyses pipelines are run on the detector data streams where fake signals have been injected. The number of recovered injections provides the efficiency of the search. In case of template searches, the modeled waveforms are injected to cover the parameter space. Then upper limits can be given as a function of the physical parameters. For unmodeled searches generic waveforms are injected with varying parameters. For instance, for the burst all-sky analyses, sine-Gaussian, Gaussian, ringdowns and cosmic string cusps signals are injected. Because of the unmodeled nature of the search, the upper limits are given on the rate as a function of the GW amplitude for a specific set of waveforms.

4 Selection of results

4.1 Limits on the rate of binary coalescence

The first search for gravitational waves from compact binary coalescence with the coincidence of the LIGO and Virgo data was performed on S5 and VSR1 data[19]. It covers the low-mass region (from 2 to 35 $M_\odot$). No detection resulted from this search and upper limits on the rate of compact binary coalescence were estimated. If the spin is neglected and assuming a mass of 1.35 ± 0.04 $M_\odot$ for the neutron star and 5.0 ± 1.0 $M_\odot$ for the black hole, the upper limits at 90% confidence level are:

$$\mathcal{R}^{BNS}_{90\%} = 8.7 \times 10^{-3} \mathrm{yr}^{-1} \mathrm{L}_{10}^{-1}, \quad (1)$$
$$\mathcal{R}^{BHNS}_{90\%} = 2.2 \times 10^{-3} \mathrm{yr}^{-1} \mathrm{L}_{10}^{-1}, \quad (2)$$
$$\mathcal{R}^{BBH}_{90\%} = 4.4 \times 10^{-4} \mathrm{yr}^{-1} \mathrm{L}_{10}^{-1}, \quad (3)$$

where BNS stands for binary neutron stars, BHNS for black hole neutron star binary and BBH for binary black holes. L_{10} corresponds to 10^{10} times the blue solar luminosity (typical for a galaxy) which is expected to be proportional to the binary coalescence rate (blue luminosity density [20]: (1.98×10^{-2}) L_{10} Mpc^{-3}). Upper limits can also be produced in mass bins and are presented on Figure 1.

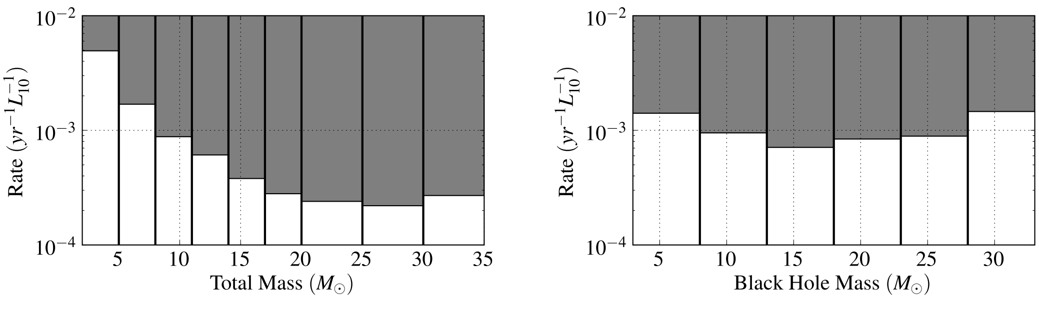

Figure 1: The 90% rate upper limits as a function of mass. The first figure gives the upper-limit on the rate of coalescence from BBH system as a function of the total mass of the system. The second figure gives the BHNS upper-limit as a function of black hole mass, assuming a fixed neutron star mass of 1.35 $M_\odot$.

Recently, the high-mass search (from 25 to 100 $M_\odot$) has also been completed and full coalescence waveforms have been used [21]. The analysis has been performed only on LIGO data since the Virgo sensitivity was not sufficient for these high mass systems during VSR1. Upper limits have been placed on the merger rate of binary black holes as a function of the component masses. For example, for two black holes with a component mass between 19 and 28 $M_\odot$ the merger rate should not exceed 2.0 Myr^{-1} Mpc^{-3} at 90 % confidence.

4.2 All-sky burst search

The all-sky search for unmodeled gravitational-wave bursts has been performed on the LIGO and Virgo data for S5 and VSR1 science runs [22]. This is a null result for a detection and upper limits have been estimated in terms of an event rate versus strength for several types of plausible burst waveforms as presented on Figure 2. The signal strength is measured with $h_{\rm rss}$ defined as:

$$h_{\rm rss} = \sqrt{\int_{-\infty}^{+\infty} dt\ (|h_+(t)|^2 + |h_\times(t)|^2)}. \qquad (4)$$

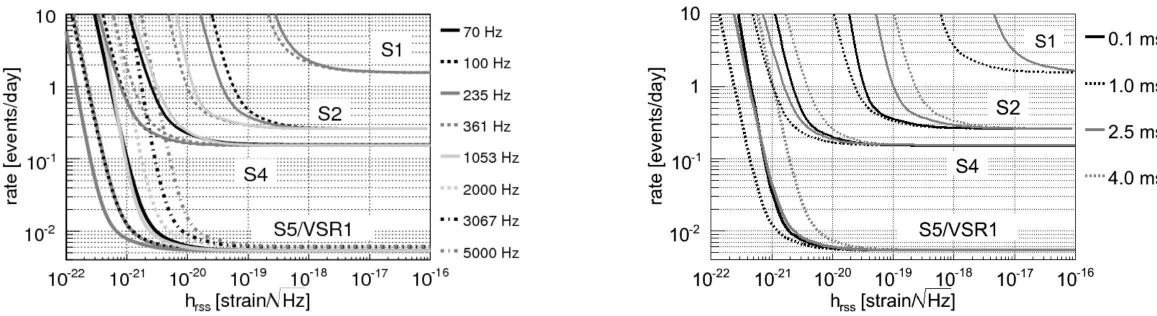

Figure 2: Selected exclusion diagrams showing the 90% confidence rate limit as a function of signal amplitude for sine-Gaussian with a quality factor of 9 and various frequencies (left) and Gaussian of different widths (right) waveforms for the results of the entire S5 and VSR1 runs compared to the results reported with the previous runs (S1, S2, and S4).

4.3 GW associated to neutron stars

There are several new LIGO/Virgo results dealing with the physics of neutron stars. The search for GW associated with the timing glitch of the Vela pulsar (PSR B083345) has recently been published [23]. Upper limits have been placed on the peak intrinsic strain amplitude of gravitational wave ring-down signals, depending on which spherical harmonic mode is excited as shown in Table 1.

Spherical Harmonic Indices	$h^{90\%}_{2m}$	$E^{90\%}_{2m}$ (erg)
$l=2, m=0$	1.4×10^{-20}	5.0×10^{44}
$l=2, m=\pm1$	1.2×10^{-20}	1.3×10^{45}
$l=2, m=\pm2$	6.3×10^{-21}	6.3×10^{44}

Table 1: The Bayesian 90% confidence upper limits on the intrinsic strain amplitude and energy associated with each spherical harmonic mode of oscillation assuming only a single harmonic (i.e. value of $|m|$) is excited.

An external triggered search has been conducted on electromagnetic triggers from six magnetars which are neutron stars powered by extreme magnetic fields [24]. These rare objects are characterized by repeated and sometimes spectacular gamma-ray bursts which could also be a source of GW. The upper limits for band- and time-limited white noise bursts in the detector sensitive band, and for f-mode ringdowns (at 1090 Hz), are $3.0\times10^{44}d_1^2$ erg and $1.4\times10^{47}d_1^2$ erg respectively, where $d_1 = d_{0501}/1\mathrm{kpc}$ and d_{0501} is the distance to SGR 0501+4516 which is likely to be ~ 1 kpc from Earth. These limits on GW emission from f-modes are an order of magnitude lower than any previous results, and approach the range of electromagnetic energies seen in SGR giant flares for the first time.

4.4 *Cosmic string upper limits*

The burst group tries to constrain the cosmic string parameter space by looking for GW emitted by cuspy features of oscillating loops [25]. The first analyses of the S4 LIGO data reports upper limits on the Gμ-ε plane where Gμ is the string tension and ε is a parameter for the loop size. Figure 3 shows the region of the parameter space which can be rejected for a cosmic string reconnection probability of 10^{-3}. The up-coming analysis of S5/S6-VSR1/VSR2/VSR3 should be able to place the most stringent limits on the cosmic string models.

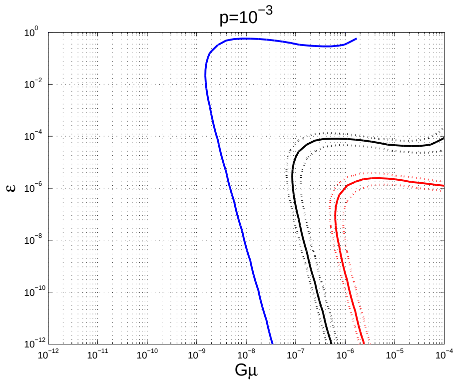

Figure 3: Plot of the upper-limit results of the S4 cosmic string analysis for a reconnection probability of 10^{-3}. Areas to the right of the red curves show the regions excluded at the 90% level. The dotted curves indicate the uncertainty. The black and blue curves limit the regions of parameter space unlikely to result in a cosmic string cusp event detected in S4: a cosmic string network with model parameters in these regions would result in less than one event (on average) surviving the search. The black curve was computed using the efficiency for all recovered injections. The blue curve shows regions of parameter space unlikely to result in a cosmic string cusp being detected in a year long search with the initial LIGO sensitivity estimate.

5 Conclusion

Searches for GW transient signals in Virgo and LIGO data have reached maturity. No GW detection can be claimed yet but significant astrophysical upper limits can be extracted from the data covering a large variety of sources. The data-taking campaigns are now over for the first generation of GW detectors but some more analysis results are expected to be released in the next months. The most recent data of S6/VSR2-3 are being analyzed and new results are about to be published.

The second generation of detectors is now in preparation and the GW science should resume in 2015. With an increased sensitivity of about a factor 10, we should expect to extend the visible volume of sources by a factor 1000. This offers a great opportunity for a detection. Even with the most pessimistic scenarios, advanced detectors should be able to detect GW. For instance, it is reasonable to expect a rate for binary neutron star coalescences of about 40 events per year.

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